Transportation Safety Board of Canada
Bureau de la sécurité des transports du Canada

OPERATIONAL SERVICES BRANCH

ENGINEERING LABORATORY REPORT

LP168/2013

Metallurgical Analysis of Tank Car Coupons

Montreal, Maine & Atlantic Railway Train, MMA 2

Date of Occurrence: 06-Jul-2013

ATTENTION:

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1.0 INTRODUCTION

1.1 Description of Occurrence

1.1.1 On 06 July 2013, a unit train carrying petroleum crude oil operated by Montreal, Maine & Atlantic Railway derailed in Lac-Mégantic, Quebec. Numerous tank cars ruptured and a fire ensued.

1.2 Engineering Services Requested

1.2.1 A request was received from the Transportation Safety Board of Canada (TSB) Eastern Regional Operations - Rail/Pipeline office to perform a metallurgical analysis of coupons recovered from selected tank cars.

1.3 Parts Received

1.3.1 Coupons were obtained from 9 derailed tank cars during the field examination. Table 1 summarizes the relevant tank car information. At least one representative tank car from each builder was sampled.

Table 1: Parts Received

Car field number[1]	Position in consist	Car initial	Car number	Owner reporting mark[2]	Builder[3]	Number of coupons
8	10	WFIX	130682	FURX	Trinity Tank Car	2
9	11	TILX	316641	TILX	Trinity Tank Car	2
15	17	ACFX	79709	NATX	ACF Industries	2
20	26	PROX	44293	PROX	Union Tank Car	2
24	25	ACFX	76605	NATX	ACF Industries	1
34	31	WFIX	130571	FURX	Trinity Tank Car	1
40	42	CTCX	735572	CEFX	ARI	2
58	63	NATX	310515	NATX	Gunderson	2
59	58	ACFX	79383	NATX	ACF Industries	2

1.3.2 Figures 1 through 9 are photographs that show the coupons as marked on the cars. Coupons were taken from locations with as little impact and fire damage as possible, except for car WFIX 130571 from which a coupon was purposely taken from an area with extensive fire damage that contained a burn-through[4] (Figure 6). The marked sections of cars were cut out using hydraulic shears before the cars were scrapped. Since hot work was not permitted on the occurrence site due to the fire hazard, an external company was contracted to cut circular coupons from the sheared-off sections of tank car using water-jet equipment. Figure 1a is a representative example of a sheared-off section of tank car after the circular

[1] Number assigned by remediation contractor
[2] From Railinc Umler Equipment Management Information System
[3] From AAR Application for Approval and Certificate of Construction
[4] A perforation due to fire damage

coupon was cut out. Table 2 summarizes the identification and origin of each coupon. Figure 10 shows the water jet-cut coupons as received at the TSB Engineering Laboratory.

Table 2: Coupon Identification and Location

Coupon identification	Car initial	Car number	Coupon location[5]
8H	WFIX	130682	B end head
8S	WFIX	130682	Shell ring 2
9H	TILX	316641	A end head
9S	TILX	316641	Shell ring 5
15H	ACFX	79709	A end head
15S	ACFX	79709	Shell ring 2
20H	PROX	44293	B end head
20S	PROX	44293	Shell ring 2
24H	ACFX	76605	B end head[6]
34S	WFIX	130571	Shell ring 5
40H	CTCX	735572	A end head
40S	CTCX	735572	Shell ring 6
58H	NATX	310515	B end head
58S	NATX	310515	Shell ring 1
59H	ACFX	79383	A end head
59S	ACFX	79383	Shell ring 2

1.4 Material Requirements for Subject Tank Cars

1.4.1 Table 3 summarizes the material type, grade and thickness indicated on the Application for Approval and Certificate of Construction of the subject tank cars. The tensile and chemical composition requirements for the specified tank car steels are summarized in Tables 4 and 5, respectively.

1.4.2 The heads of 4 cars (WFIX 130582, TILX 316641, PROX 44293 and WFIX 130571) were made of non-normalized ASTM A516 Grade 70 steel whereas the heads of 2 cars (CTCX 735572 and NATX 310515) were made of normalized ASTM A516 Grade 70 steel. The heads of 3 cars (ACFX 79709, ACFX 76605 and ACFX 79383) were made of non-normalized ASTM A515 Grade 70 steel.

1.4.3 All of the shells were made of non-normalized AAR TC128 Grade B steel except for car NATX 310515, the shell of which was made of normalized AAR TC128 Grade B steel.

[5] Shell rings numbered starting from B end
[6] Head and shell coupons had been marked on car ACFX 76605 but the shell coupon was not recovered

Table 3: Material Requirements for Subject Tank Cars

Car initial	Car number	Heads		Shell	
		Steel type and grade	Nominal thickness (inch)	Steel type and grade	Nominal thickness (inch)
WFIX	130682	ASTM A516[7] Grade 70	7/16	AAR TC128[8] Grade B	7/16
TILX	316641	ASTM A516 Grade 70	7/16	AAR TC128 Grade B	7/16
ACFX	79709	ASTM A515[9] Grade 70	15/32	AAR TC128 Grade B	7/16
PROX	44293	ASTM A516 Grade 70	15/32	AAR TC128 Grade B	7/16
ACFX	76605	ASTM A515 Grade 70	15/32	AAR TC128 Grade B	7/16
WFIX	130571	ASTM A516 Grade 70	7/16	AAR TC128 Grade B	7/16
CTCX	735572	ASTM A516 Grade 70 normalized	7/16	AAR TC128 Grade B	7/16
NATX	310515	ASTM A516 Grade 70 normalized	0.443	AAR TC128 Grade B normalized	0.438
ACFX	79383	ASTM A515 Grade 70	15/32	AAR TC128 Grade B	7/16

Table 4: Tensile Requirements for Tank Car Steels

Specification	Minimum yield strength (psi)	Tensile strength (psi)	Minimum elongation in 2 inches (%)
ASTM A515 Grade 70	38,000	70,000 to 90,000	21
ASTM A516 Grade 70	38,000	70,000 to 90,000	21
AAR TC128 Grade B	50,000	81,000 to 101,000	22.0 min.

[7] ASTM A516/A516M-10 Standard Specification for Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service
[8] AAR TC128 Specification for High-Strength Carbon Manganese Steel Plates for Tank Cars
[9] ASTM A515/A515M-10 Standard Specification for Pressure Vessel Plates, Carbon Steel, for Intermediate- and Higher-Temperature Service

Table 5: Chemical Composition Requirements for Tank Car Steels

Element	Chemical requirements		
	AAR TC128 Grade B[10]	ASTM A516 Grade 70[11]	ASTM A515 Grade 70[12]
Carbon (max %)	0.26	0.25 [A]	0.31 [B]
Manganese (%)	1.00-1.70 [A]	0.79-1.26 [C]	1.30 [C]
Phosphorus (max %)	0.025	0.025	0.025
Sulfur (max %)	0.015	0.015	0.025
Silicon (%)	0.13-0.45 [A]	0.15-0.45	0.13-0.45
Vanadium (max %)	0.084	0.04 [D]	0.04 [D]
Copper (max %)	0.35	0.35	0.43 [D]
Nickel (max %)	No limit	0.43 [D]	0.43 [D]
Chromium (max %)	No limit	0.34 [D]	0.34 [D]
Molybdenum (max %)	No limit	0.13 [D]	0.13 [D]
Aluminum (%)	0.015-0.060	0.015-0.060	Not specified
Niobium (max %)	0.03 [D]	0.03 [D]	0.03 [D]
Titanium (max %)	0.020	0.020	0.04 [D]
Boron (max %)	0.0005	0.0005	0.0015 [D]
Nitrogen (max %)	0.012	0.012	Not specified
Tin (max %)	0.020	0.020	Not specified
C_{Eq} (max %) [E]	0.55	0.45	0.47 [F]
Cu+Ni+Cr+Mo (max %)	0.65	0.65	1.00 [D]
Nb+V+Ti (max %)	0.11	0.11	Not specified
Ti/N (max ratio)	4.0	4.0	Not specified

[A] for plate ≤ 3/4 inch thick
[B] 1 inch and under
[C] for each reduction of 0.01 percentage point below the specified maximum for carbon, an increase of 0.06 percentage point above the specified maximum for manganese is permitted, up to a maximum of 1.60%
[D] per ASTM A20/A20M Table 1
[E] $C_{Eq} = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15$ [13]
[F] per ASTM A20/A20M Table S20.1

2.0 <u>EXAMINATION</u>

2.1 Chemical Analysis

2.1.1 Samples approximately 1 by 2 inches in size were cut from each tank car coupon at the locations indicated by the dashed red lines in Figure 10. The cut-out

[10] AAR Manual of Standards and Recommended Practices – Specifications for Tank Cars, Table M2 Chemical Requirements for AAR TC128 Grade B steel - Product Analysis, 10/2007, page C-III [M-1002] 338
[11] AAR Manual of Standards and Recommended Practices – Specifications for Tank Cars, Table M11 Supplemental Chemical Requirements for ASTM A516 Grade 70 – Product Analysis, 10/2007, page C-III [M-1002] 345
[12] ASTM A515/A515M-10 Standard Specification for Pressure Vessel Plates, Carbon Steel, for Intermediate- and Higher-Temperature Service
[13] Carbon equivalent calculated in accordance with ASTM A20/A20M section S20.2

samples are shown in Figure 11. The samples were sent to an external laboratory[14] for chemical analysis in accordance with ASTM E415-08[15] and ASTM E1019-11.[16] The detailed chemical analysis results are presented in Appendix A (see Tables A-1 through A-9).

2.1.2 All of the tank car coupons, except for coupon 15S (ACFX 79709 shell), gave chemical analysis results that were in agreement with the currently applicable chemical requirements. Coupon 15S gave a Cu+Ni+Cr+Mo result of 0.74% (Table A-3), which is slightly higher than the maximum Cu+Ni+Cr+Mo limit of 0.65% for TC128 Grade B steel (Table 5). However, tank car ACFX 79709 was ordered in 1979 and the specification had no requirement for a maximum Cu+Ni+Cr+Mo content at that time. Therefore coupon 15S would have met the chemical requirements applicable when the tank car was ordered.

2.2 Thickness Measurements

2.2.1 Table 6 summarizes the thickness results obtained on the tank car coupons. Coupon 34S was not measured since it was visibly eroded due to fire damage. The permissible variation in thickness for plate with a specified thickness of 0.438 (7/16) to 0.5 inch ranges from 0.03 to 0.06 inch, depending on the width of the plate.[17] The subject tank car coupons met this tolerance requirement.

2.3 Metallurgical Examination

2.3.1 Metallurgical cross-sections were prepared from the coupons to examine their microstructure. For shell coupons, the cross-sections were taken parallel to the tank's longitudinal axis i.e. transverse to the final rolling direction of the plate. For head coupons, the cross-sections were taken parallel to the vertical axis of the tank (the final rolling direction of head plates relative to the tank was unknown). Figures 12 through 21 display representative micrographs of the cross-sections.

2.3.2 The microstructure of head and shell coupons taken from cars WFIX 130682, TILX 316641, ACFX 79709, PROX 44293, ACFX 79383 and the shell coupon from car CTCX 735572 was composed of equiaxed or slightly elongated ferrite (white constituent) and pearlite[18] (dark constituent) (Figures 12, 13, 14, 15, 21 and 19). Coupons 20S (CTCX 735572 shell) and 59H (ACFX 79383 head) also contained acicular ferrite grains (Figures 15d and 21c), suggesting the probable presence of bainite. Examination at higher magnification in a scanning electron microscope (SEM) revealed that the pearlite was lamellar with no visible spheroidizing.[19] The cross-sections exhibited varying degrees of ferrite-pearlite

[14] Exova Burlington Laboratory accredited to ISO/IEC 17025
[15] ASTM E415-08 Standard Test Method for Atomic Emission Vacuum Spectrometric Analysis of Carbon and Low-Alloy Steel
[16] ASTM E1019-11 Standard Test Methods for Determination of Carbon, Sulfur, Nitrogen, and Oxygen in Steel, Iron, Nickel, and Cobalt Alloys by Various Combustion and Fusion Techniques
[17] ASTM A20/A20M-11 Standard Specification for General Requirements for Steel Plates for Pressure Vessels, Table A1.1
[18] Pearlite is a mixture of ferrite and cementite (iron carbide) in which the two phases are formed from austenite in alternating lamellar pattern
[19] Spheroidizing occurs as a result of heating and cooling to produce a globular form of carbide in steel

banding.[20] Overall these microstructures were consistent with the typical microstructure for non-normalized (as-rolled) steel plates. Coupons 15H (ACFX 79709 head) and 24H (ACFX 76605 head) exhibited visibly larger grains and pearlite with coarser inter-lamellar spacing than the other as-rolled steel coupons in this group.

2.3.3 The microstructure of coupons 58H and 58S (NATX 310515 head and shell) was composed of fine-grained ferrite and lamellar pearlite, with some banding (Figure 20), consistent with a normalized plate steel. Coupon 40H (CTCX 735572 head) was also made of normalized steel but its microstructure was visibly coarser (Figure 19a, 19c and 19e).

Table 6: Thickness Results

Coupon identification	Car initial, number and coupon location	Measured thickness (inch)	Nominal thickness (inch)
8H	WFIX 130682 head	0.532	0.438
8S	WFIX 130682 shell	0.455	0.438
9H	TILX 316641 head	0.515	0.438
9S	TILX 316641 shell	0.455	0.438
15H	ACFX 79709 head	0.465	0.469
15S	ACFX 79709 shell	0.450	0.438
20H	PROX 44293 head	0.477	0.469
20S	PROX 44293 shell	0.455	0.438
24H	ACFX 76605 head	0.465	0.469
34S	WFIX 130571 shell	not determined	0.438
40H	CTCX 735572 head	0.473	0.438
40S	CTCX 735572 shell	0.448	0.438
58H	NATX 310515 head	0.456	0.443
58S	NATX 310515 shell	0.437	0.438
59H	ACFX 79383 head	0.477	0.469
59S	ACFX 79383 shell	0.457	0.438

2.3.4 Figures 17 and 18 show the microstructure of coupon 34S (WFIX 130571 shell). Two cross-sections were prepared from this coupon: the first through the edge of the burn-through (Figure 17) and the second a few centimeters away from the burn-through (Figure 18). Both cross-sections revealed significant microstructure variations across the thickness of the plate (Figures 17a and 18a). There was a visible reduction of the amount of pearlite (dark constituent) near the outer surface whereas the material adjacent to the inner surface was almost fully pearlitic. Such variations were not observed on the other tank car coupons.

[20] An inhomogeneous distribution of ferrite and pearlite aligned in filaments or plates parallel to the direction of working

2.3.5 On the first cross-section (through the edge of the burn-through), the material adjacent to the inner surface had a lamellar pearlite microstructure with blocky ferrite grains decorating the boundaries of the large prior austenite grains (Figures 17b and 17c). On the second cross-section (away from the burn-through), the material adjacent to the inner surface also exhibited a fully pearlitic microstructure but the prior austenite grain boundaries were decorated with a continuous film of carbide phase (most probably cementite) - see Figures 18b, 18c, 18d and 18e. These observations suggest that the region adjacent to the inner surface was significantly enriched with carbon. The carbon content corresponding to a fully pearlitic microstructure is about 0.8 wt.%,[21] as compared with the initial carbon concentration of 0.11 wt.% (Table A-6). It is considered most probable that this carbon enrichment occurred when the steel was exposed to a carbon-rich environment at elevated temperatures during the post-derailment fire. The crude oil in the tank car likely acted as a supply of carbon for absorption and diffusion into the steel.

2.3.6 The middle portions of the coupon 34S cross-sections exhibited amounts of ferrite and pearlite phases similar to those observed in other cross-sections of as-rolled TC128 Grade B steel (for example coupon 8S). However, the coupon 34S cross-sections had visibly larger grain size, as demonstrated by comparing the grain size on Figures 12b and 12f (coupon 8S) with Figures 17d, 17e, 18f and 18g (coupon 34S). This is consistent with the steel having been overheated during the exposure to the post-derailment fire.

2.3.7 The microstructure at the outer surface of coupon 34S was composed mainly of ferrite, with only a small amount of pearlite. The outer surface was covered with an irregular layer of oxide. Figure 17f shows a representative cross-section through this oxide. Energy dispersive x-ray spectroscopy (EDS) indicated it was composed of iron oxide (see area 1 on Figures 17f and 17g) and iron-silicon oxide (see area 2 on Figures 17f and 17g). The above observations indicate that the outer surface of coupon 34S was both decarburized and oxidized. When steel is exposed to an environment containing oxygen and water vapour at high temperature (as would have been present during the response to the post-derailment fire), the carbon atoms near the surface react with the oxygen and water vapour, causing a reduction of the surface carbon content and consequently, an increase of ferrite content. The iron atoms in the steel also react with the oxygen and water vapour to form iron oxide at the surface.

2.4 Hardness Tests

2.4.1 Rockwell B hardness measurements were performed on the metallurgical cross-sections. Hardness was also measured on a second set of samples cut at 90 degrees to the orientation of the metallurgical cross-sections (i.e. parallel to the final rolling direction for shell coupons and parallel to the horizontal axis of the tank for head coupons, see paragraph 2.3.1). The results are summarized in Table 7. The tensile strength requirement for the AAR TC128 Grade B steel used for the shells is 81,000 to 101,000 psi, corresponding to an approximate hardness

[21] W. F. Smith, *Structure and Properties of Engineering Alloys*, (McGraw-Hill, 1981), page 7

requirement of 84 to 95.5 HRBW.[22] The shell coupons met this requirement except for coupons 9S, 15S and 40S that gave results slightly below the 84 HRBW limit. The tensile strength requirement for the ASTM A515 Grade 70 and ASTM A516 Grade 70 steels used for the heads is 70,000 to 90,000 psi. This corresponds to an approximate hardness requirement of 79 to 91 HRBW. Head coupons 9H, 20H and 59H met this requirement whereas coupons 8H, 15H, 24H, 40H and 58H gave results slightly below the 79 HRBW limit.

Table 7: Rockwell B Hardness Results

Coupon identification	Car initial, number and coupon location	Average hardness (HRBW)	
		Metallurgical cross-section	90º to metallurgical cross-section
8H	WFIX 130682 head	78	76
8S	WFIX 130682 shell	85	82
9H	TILX 316641 head	81	79
9S	TILX 316641 shell	85	83
15H	ACFX 79709 head	79	76
15S	ACFX 79709 shell	85	84
20H	PROX 44293 head	82	81
20S	PROX 44293 shell	95	95
24H	ACFX 76605 head	76	73
34S	WFIX 130571 shell	88	not determined
40H	CTCX 735572 head	77	76
40S	CTCX 735572 shell	83	82
58H	NATX 310515 head	80	78
58S	NATX 310515 shell	87	85
59H	ACFX 79383 head	87	86
59S	ACFX 79383 shell	91	90

2.5 Tensile Tests

2.5.1 Tensile testing of selected tank car coupons was conducted by an external laboratory[23] in accordance with ASTM A370-12a. Tensile samples were machined with their longitudinal axis parallel to the tank's longitudinal axis (shell coupons) or to its vertical axis (head coupons). The gauge length was 2 inches and the nominal gauge width was 0.5 inch. Three samples were tested for each coupon and the results are presented in Tables 8 (head coupons) and 9 (shell coupons).

2.5.2 All of the head coupons met the tensile requirements for the specified ASTM A515 Grade 70 and ASTM A515 Grade 70 steels (Table 8). All of the shell coupons met the tensile requirements for the specified AAR TC128 Grade B steel, except for coupon 40S (CTCX 735572) that had 2 samples (40S-2 and 40S-3)

[22] Conversion of tensile strength to approximate Rockwell B hardness in accordance with ASTM A370-12a Standard Test Methods and Definitions for Mechanical Testing of Steel Products, Table 3
[23] Exova Burlington Laboratory accredited to ISO/IEC 17025

with ultimate tensile strength (UTS) results marginally below the minimum requirement (Table 9).

2.5.3 Coupons made of non-normalized steel gave tensile results that were generally comparable to those obtained from normalized steel coupons (Tables 8 and 9).

Table 8: Tensile Results – Head Coupons

Car initial and number	Steel type and grade	Sample id.	0.2% yield stress (psi)	Ultimate tensile strength (psi)	Elongation (%)
TILX 316641	ASTM A516 Grade 70 non-normalized	9H-1	51,600	72,900	38
		9H-2	53,400	75,300	36
		9H-3	52,300	74,800	35
PROX 44293	ASTM A516 Grade 70 non-normalized	20H-1	48,400	76,200	35
		20H-2	46,300	76,800	33
		20H-3	49,900	75,700	33
CTCX 735572	ASTM A516 Grade 70 normalized	40H-1	44,000	71,400	38
		40H-2	41,100	71,100	34
		40H-3	41,900	71,400	36
NATX 310515	ASTM A516 Grade 70 normalized	58H-1	46,900	73,600	36
		58H-2	52,600	74,800	34
		58H-3	51,400	75,000	34
ACFX 79383	ASTM A515 Grade 70 non-normalized	59H-1	48,100	81,500	24
		59H-2	60,300	85,800	29
		59H-3	61,600	86,200	29
Tensile requirements per ASTM A515-70 and ASTM A516-70 (see Table 4)			min 38,000	70,000 to 90,000	min 21

Table 9: Tensile Results – Shell Coupons

Car initial and number	Steel type and grade	Sample id.	0.2% yield stress (psi)	Ultimate tensile strength (psi)	Elongation (%)
TILX 316641	AAR TC128 Grade B non-normalized	9S-1	54,100	81,600	30
		9S-2	51,700	81,600	30
		9S-3	52,100	82,000	34
PROX 44293	AAR TC128 Grade B non-normalized	20S-1	67,800	98,400	24
		20S-2	71,500	97,500	22
		20S-3	70,300	97,400	22
CTCX 735572	AAR TC128 Grade B non-normalized	40S-1	52,600	81,000	34
		40S-2	53,400	80,700	32
		40S-3	50,600	80,300	32
NATX 310515	AAR TC128 Grade B normalized	58S-1	62,500	84,500	28
		58S-2	62,900	84,900	28
		58S-3	62,800	85,000	30
ACFX 79383	AAR TC128 Grade B non-normalized	59S-1	66,400	89,700	26
		59S-2	68,600	91,400	26
		59S-3	67,600	91,300	26
Tensile requirements per AAR TC128-B (see Table 4)			min 50,000	81,000 to 101,000	min 22.0

3.0 DISCUSSION

3.1 The tank car coupons gave chemical analysis results that were consistent with the currently applicable chemical requirements, except for coupon 15S (ACFX 79709 shell) which had a slightly enhanced amount of the sum concentration of 4 metallic elements (the concentrations of these elements taken separately met the current specification requirements). However, this coupon would have met the chemical requirements applicable when tank car ACFX 79709 was ordered.

3.2 The microstructure of the tank car coupons was composed primarily of ferrite and pearlite grains, with some variation of grain size and degree of ferrite-pearlite banding. Overall, the coupon microstructures were generally consistent with the microstructure expected for the specified plate steels.

3.3 Coupons 58H and 58S (NATX 310515 head and shell), which were made of normalized steels, had visibly finer grains than the other coupons, consistent with the expected effect of normalizing. During the normalizing process, the steel is reheated to form austenite, followed by air cooling through the phase transformation. This is usually done to refine the ferrite grain size and to obtain a fine pearlite structure. [24]

3.4 Coupons 15H (ACFX 79709 head), 24H (ACFX 76605 head), 40H and 40S (CTCX 735572 head and shell) had visibly larger grains and coarser pearlite than the other coupons. Discoloration indicative of fire damage was noted on the outer surface of these tank cars (see Figures 3, 5 and 7). Reheating of ferrite-pearlite steels above 600 to 700°C eventually causes a coarsening of the microstructure.[25] Ferrite grain growth takes place due to the enhanced rate of diffusion at higher temperature. The cementite particles of the pearlite phase can also coarsen and eventually become spheroidized (globular). It is considered likely that the coarser microstructures exhibited by coupons 15H, 24H, 40H and 40S were caused by the exposure to the post-derailment fire.

3.5 The Rockwell B hardness results obtained for the tank car coupons were in general agreement with the equivalent hardness limits corresponding to the tensile requirement except for some coupons that gave marginally low hardness results. As noted above, coupons 15H, 24H, 40H and 40S had visibly coarser microstructures, likely due to their exposure to the post-derailment fire. This may explain their lower hardness since grain growth results in softening of the steel. It is possible that some coarsening due to fire exposure also affected the microstructure of other coupons with lower hardness results.

3.6 Head coupons from cars TILX 316641, PROX 44293, CTCX 735572, NATX 310515 and ACFX 79383 met the tensile requirements for the specified ASTM A515 Grade 70 and ASTM A515 Grade 70 steels. The shell coupons met the tensile requirements for the specified AAR TC128 Grade B steel, except for coupon 40S (CTCX 735572) that had 2 samples with UTS results marginally below the minimum requirement. As mentioned above, the microstructure of this coupon was likely softened due to exposure to the post-derailment fire.

[24] R. W. K. Honeycombe, *Steels - Microstructure and Properties*, (Edward Arnold, UK, 1981)
[25] Ibid.

3.7 The examination of a coupon taken from a tank car with extensive fire damage revealed a carbon-enriched region at the tank's inner surface. The crude oil in the tank car likely acted as a supply of carbon for absorption and diffusion into the steel during the exposure to the post-derailment fire. High-temperature carburization attack can produce embrittlement, pitting and rapid loss of material (so-called metal dusting).[26] The outer surface of the steel was decarburized and oxidized, consistent with exposure to oxygen and/or water vapour at elevated temperature. No sign of melting was observed on the coupon cross-sections indicating that melting was not the cause of the burn-through. It is concluded that chemical reaction of the steel with the crude oil and the external environment was likely responsible for the plate erosion and loss of material causing the burn-through.

3.8 The cross-sections of the fire-damaged coupon had large grains suggesting that the steel was exposed to high temperatures in the austenite range (well above 800°C), causing significant coarsening of the austenite. This is consistent with the range of temperatures within pool fires reported in available literature (900 to 1100°C).[27]

4.0 CONCLUSION

4.1 The tank car coupons met the applicable chemical composition requirements at time of manufacture.

4.2 The tank car coupons met the current thickness requirements.

4.3 With the exception of some coupons likely affected by exposure to the post-derailment fire, the microstructure of the tank car coupons was generally consistent with the microstructure expected for the specified plate steels.

4.4 The microstructure of some coupons was likely coarsened due to exposure to high temperature during the post-derailment fire.

4.5 The tank car coupons met the specified tensile requirements except for 1 coupon (CTCX 735572 shell) which gave slightly low ultimate tensile strength results. This was likely due to softening of the steel caused by the exposure to the post-derailment fire.

4.6 Coupons made of non-normalized and normalized steels had generally similar tensile properties.

4.7 The coupon with extensive fire damage exhibited changes to its carbon content and external oxidation consistent with exposure to crude oil and air at high temperature during the post-derailment fire. The resulting chemical reactions were likely responsible for the loss of material causing the burn-through. A large grain size was observed indicating that the steel was likely exposed to temperatures well above 800°C.

[26] *Metals Handbook: Volume 13 Corrosion*, (ASM International 1987), page 1312
[27] *SFPE Handbook of Fire Protection Engineering*, 3rd Edition (National Fire Protection Association, 2002), page 3-289

4.8 The coupon examination did not find any material deficiency that could have affected the performance of the tank cars during the derailment.

(a) Sheared-off head with a round hole where the coupon has been cut out using water-jet equipment.

(b) Coupon marked on the shell.

Figure 1: Photographs showing coupons marked on tank car WFIX 130682.

(a) Coupon marked on the head.

(b) Coupon marked on the shell.

Figure 2: Photographs showing coupons marked on tank car TILX 316641.

(a) Coupon marked on the head.

(b) Coupon marked on the shell.

Figure 3: Photographs showing coupons marked on tank car ACFX 79709.

(a) Coupon marked on the head.

(b) Coupon marked on the shell.

Figure 4: Photographs showing coupons marked on tank car PROX 44293.

Figure 5: Photograph showing coupon marked on the head of tank car ACFX 76605.

Figure 6: Photograph showing the location (circled) from which a coupon was taken from tank car WFIX 130571.

Figure 7: Photograph showing coupons marked the head and shell of tank car CTCX 735572.

(a) Coupon marked on the head.

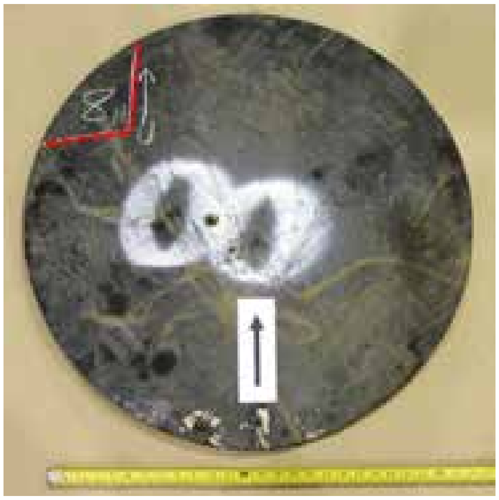
(b) Coupon marked on the shell.

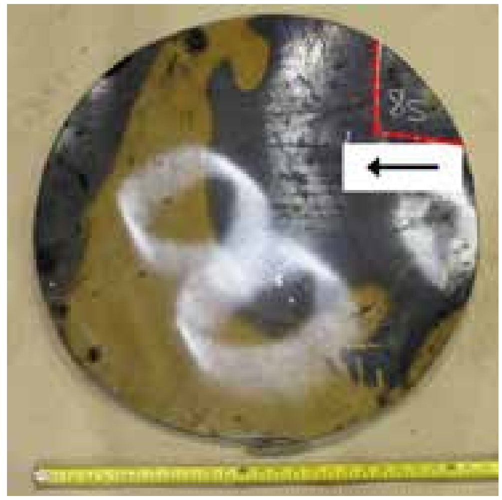
Figure 8: Photographs showing coupons marked on tank car NATX 310515.

(a) Coupon marked on the head.

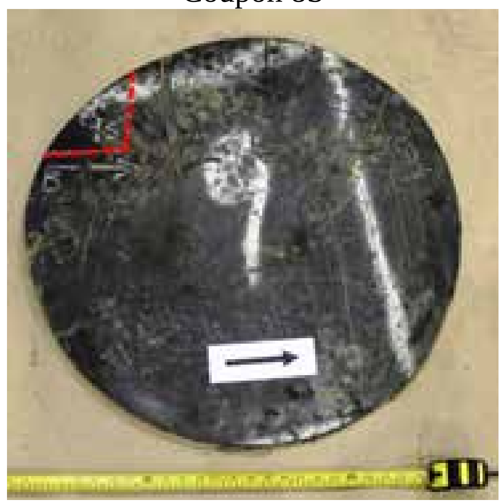
(b) Coupon marked on the shell.

Figure 9: Photographs showing the coupons marked on tank car ACFX 79383.


Coupon 8H


Coupon 8S


Coupon 9H


Coupon 9S


Coupon 15H


Coupon 15S

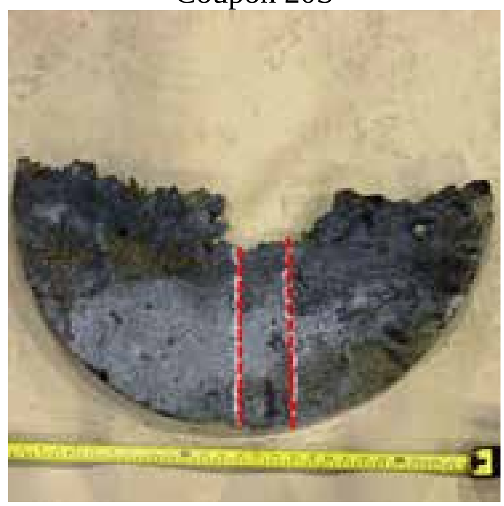
Figure 10: Photographs showing the coupons as received.

Arrows indicate the “up” direction (head coupons) or the car’s longitudinal axis (shell coupons). Dashed red lines indicate the portion used for chemical analysis, metallurgical examination and hardness testing.

Coupon 20H

Coupon 20S

Coupon 24H

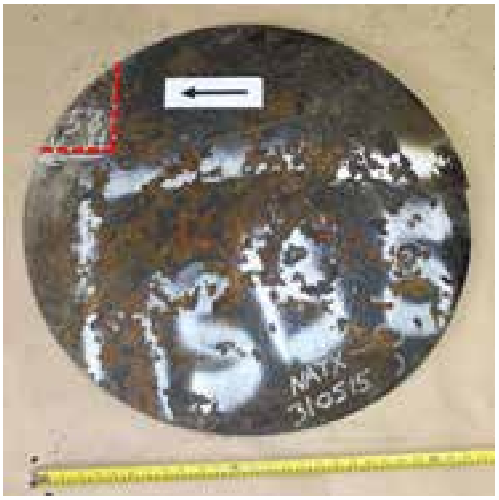


Coupon 34S

Coupon 40H

Coupon 40S

Figure 10: Photographs showing the coupons as received.
Arrows indicate the "up" direction (head coupons) or the car's longitudinal axis (shell coupons). Dashed red lines indicate the portion used for chemical analysis, metallurgical examination and hardness testing.



Coupon 58H


Coupon 58S

Coupon 59H

Coupon 59S

Figure 10: Photographs showing the coupons as received.
Arrows indicate the “up” direction (head coupons) or the car’s longitudinal axis (shell coupons). Dashed red lines indicate the portion used for chemical analysis, metallurgical examination and hardness testing.

Figure 11: Photograph showing the samples cut out of each coupon.

The smaller piece was used for chemical analysis; the larger piece for metallurgical examination and hardness testing. Arrows marked on the larger pieces indicate the vertical direction (head coupons) or the tank car's longitudinal axis (shell coupons).

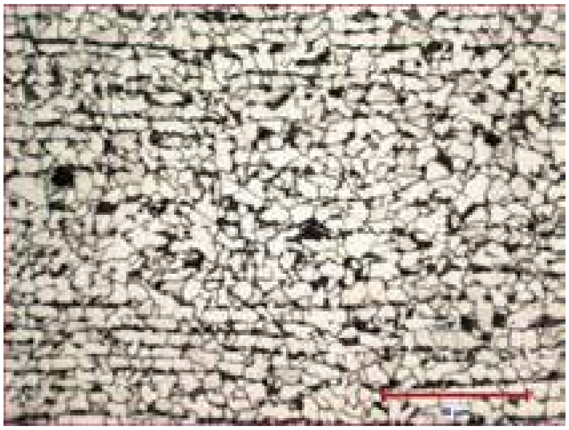
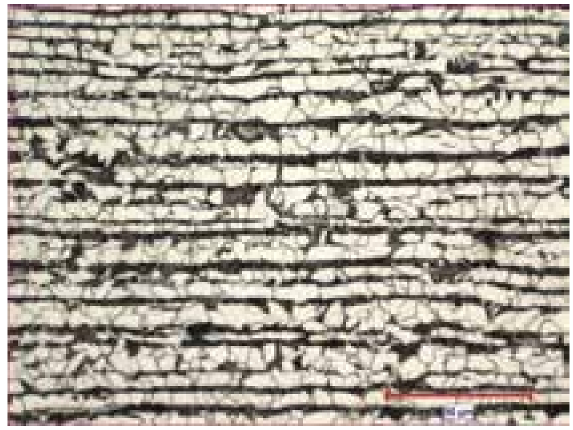
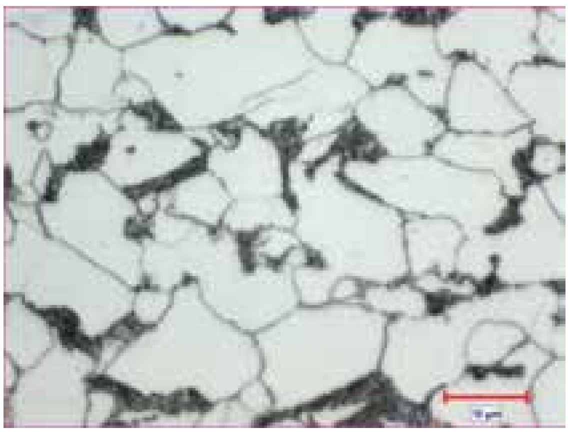
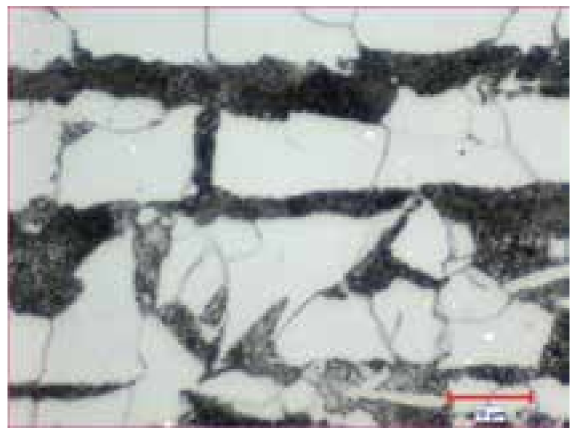
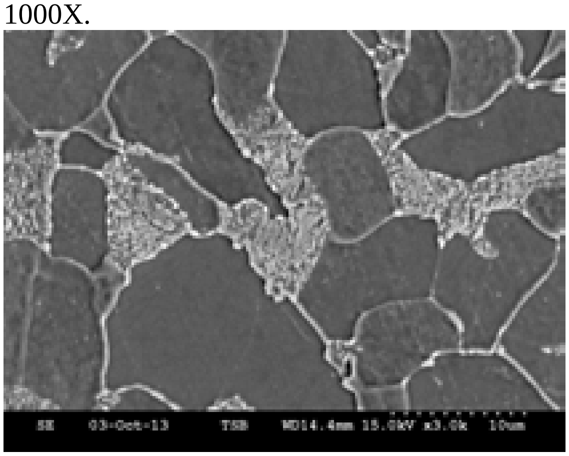
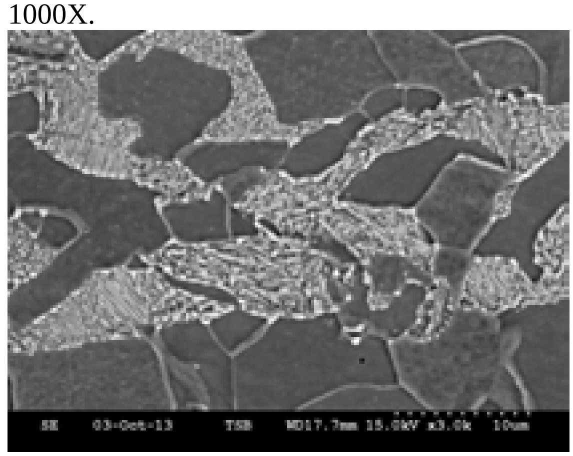
Coupon 8H – head	**Coupon 8S - shell**
 (a) Optical micrograph, original magnification 200X.	 (b) Optical micrograph, original magnification 200X.
 (c) Optical micrograph, original magnification 1000X.	 (d) Optical micrograph, original magnification 1000X.
 (e) SEM micrograph, original magnification 3000X.	 (f) SEM micrograph, original magnification 3000X.

Figure 12: Metallurgical cross-sections (Nital etch) of the WFIX 130682 coupons.

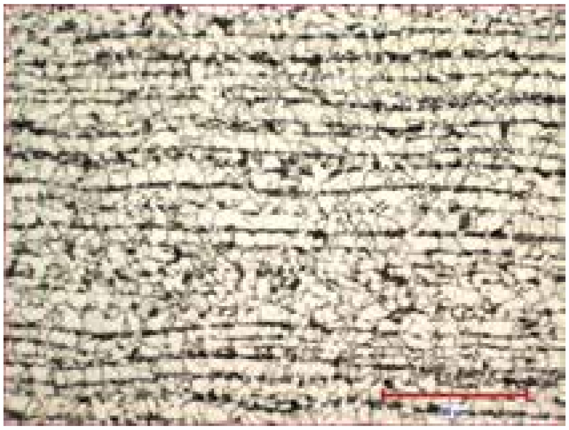
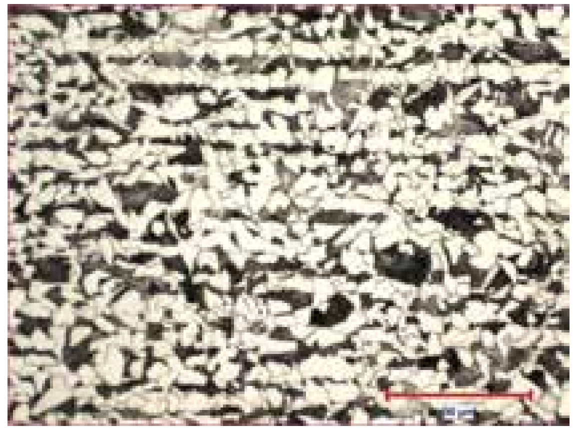
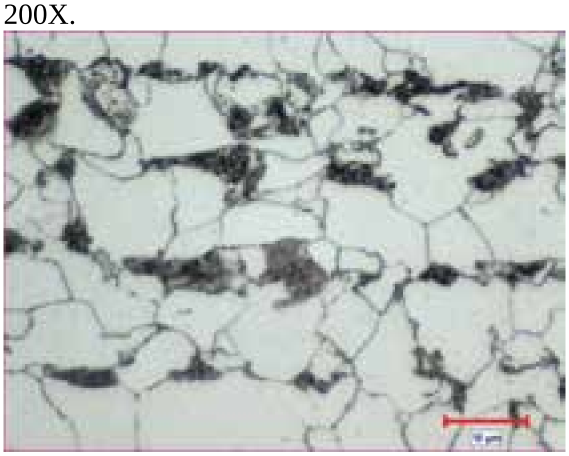
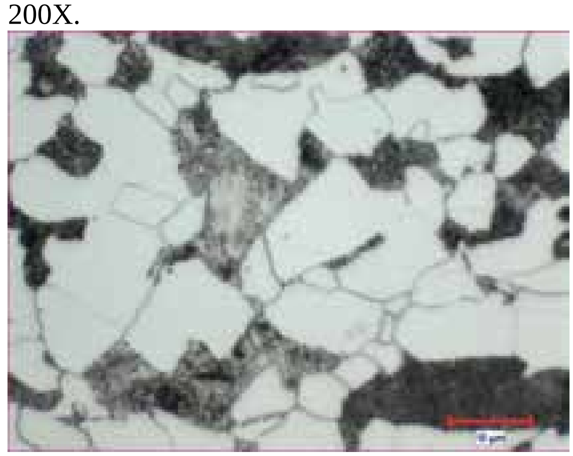
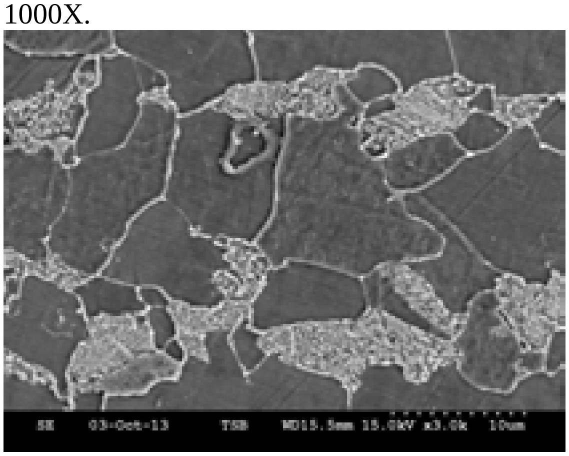
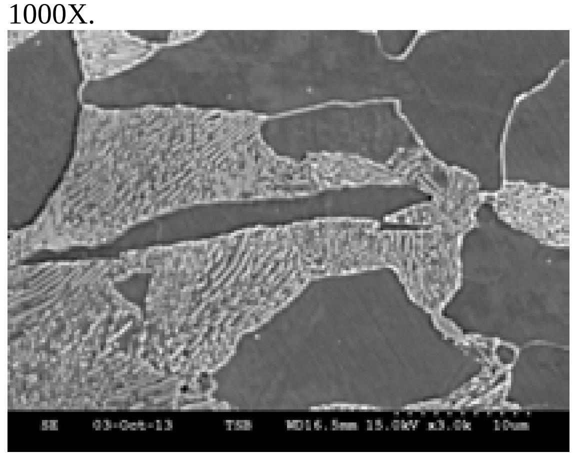
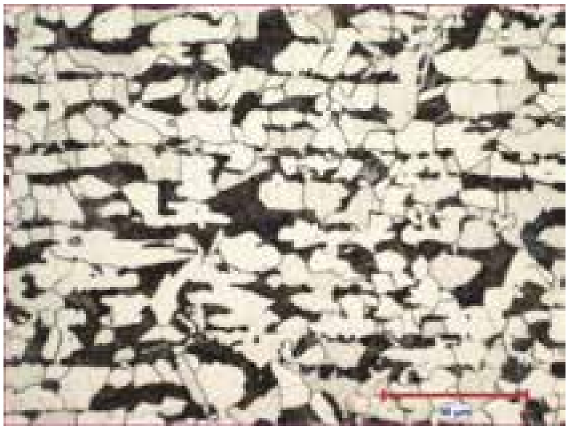
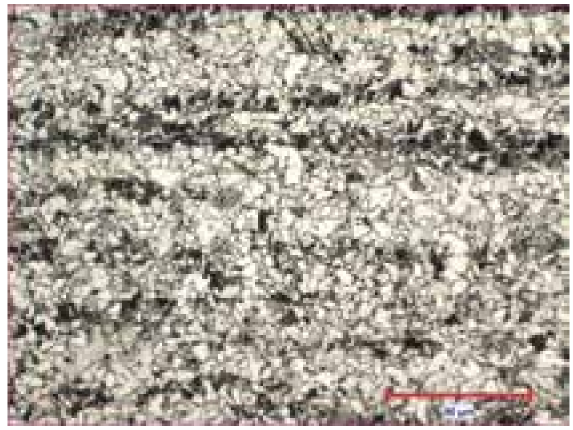
Coupon 9H - head	**Coupon 9S - shell**
 (a) Optical micrograph, original magnification 200X.	 (b) Optical micrograph, original magnification 200X.
 (c) Optical micrograph, original magnification 1000X.	 (d) Optical micrograph, original magnification 1000X.
 (e) SEM micrograph, original magnification 3000X.	 (f) SEM micrograph, original magnification 3000X.

Figure 13: Metallurgical cross-sections (Nital etch) of the TILX 316641 coupons.

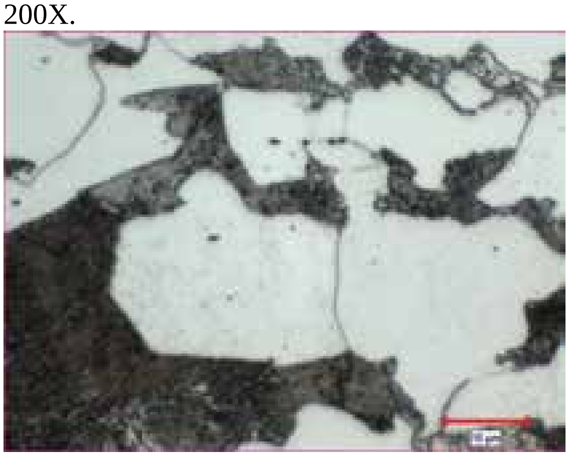
Coupon 15H - head	**Coupon 15S - shell**



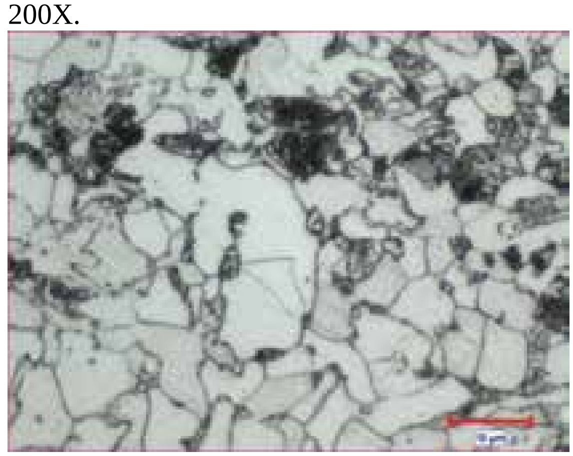
(a) Optical micrograph, original magnification 200X.



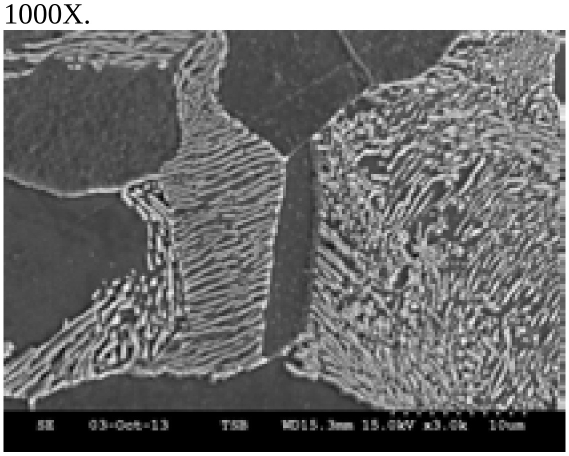
(b) Optical micrograph, original magnification 200X.



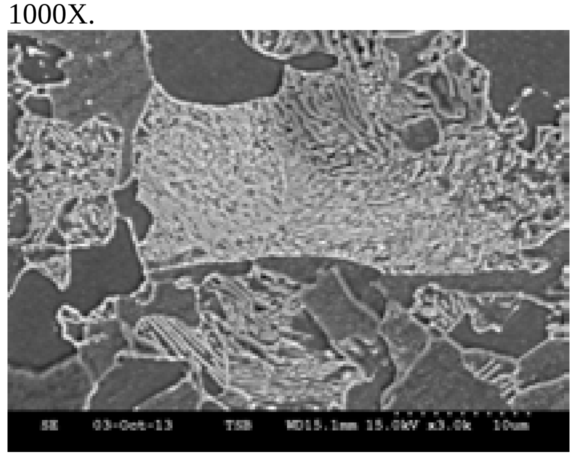
(c) Optical micrograph, original magnification 1000X.



(d) Optical micrograph, original magnification 1000X.



(e) SEM micrograph, original magnification 3000X.



(f) SEM micrograph, original magnification 3000X.

Figure 14: Metallurgical cross-sections (Nital etch) of the ACFX 79709 coupons.

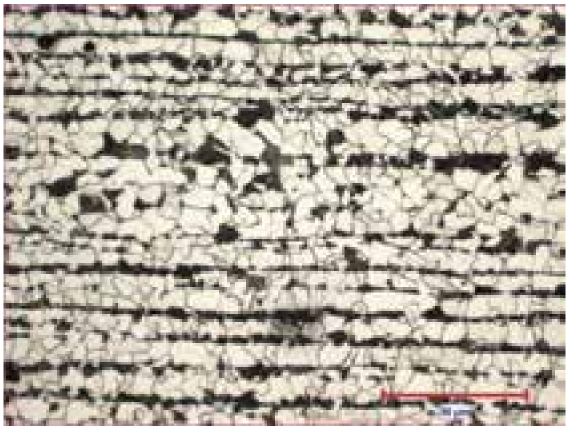
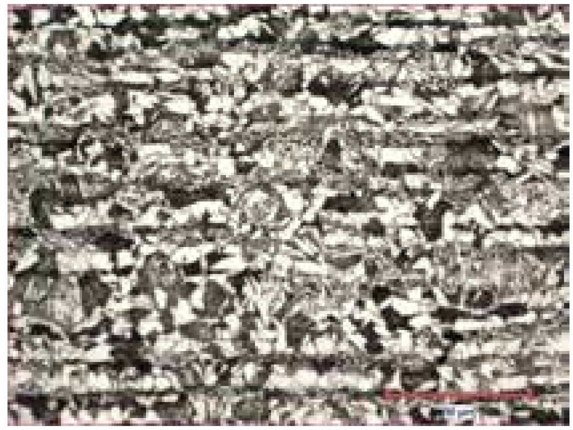
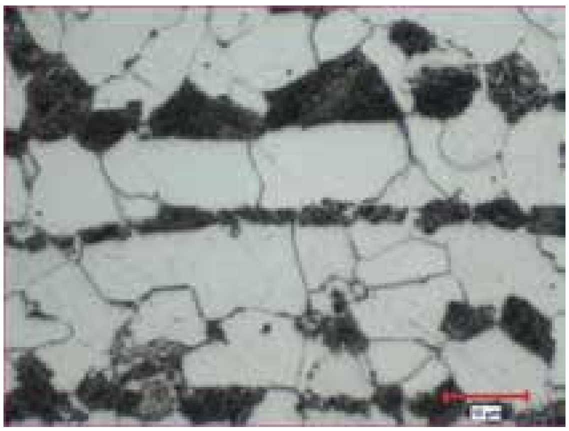
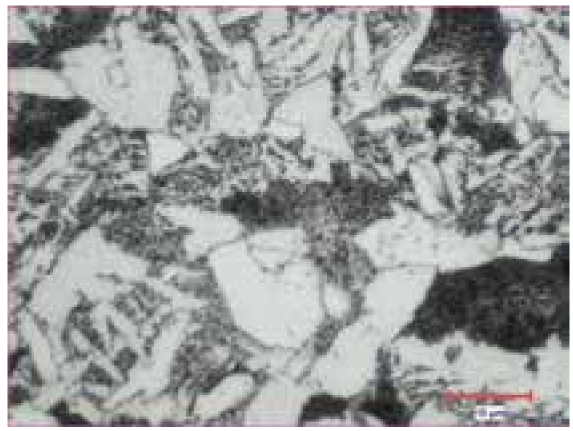
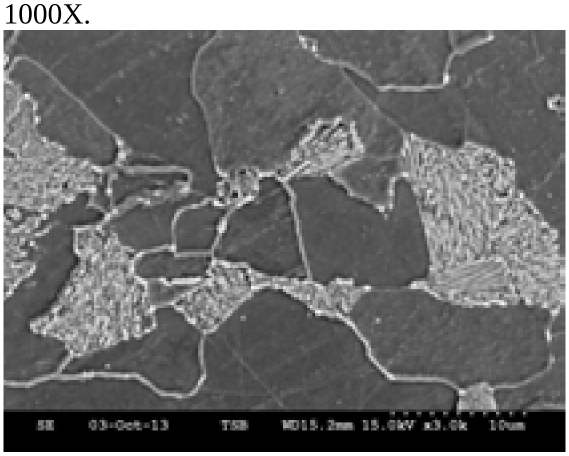
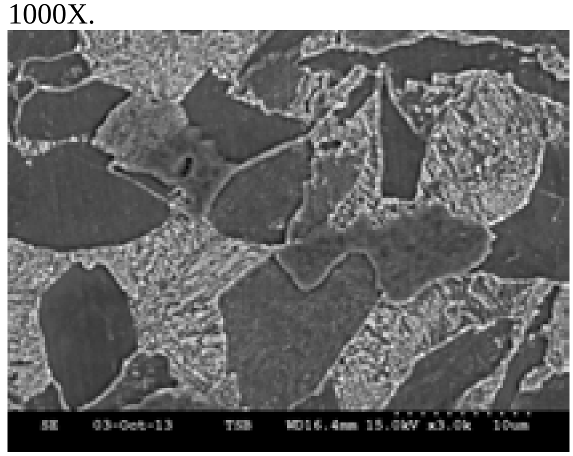
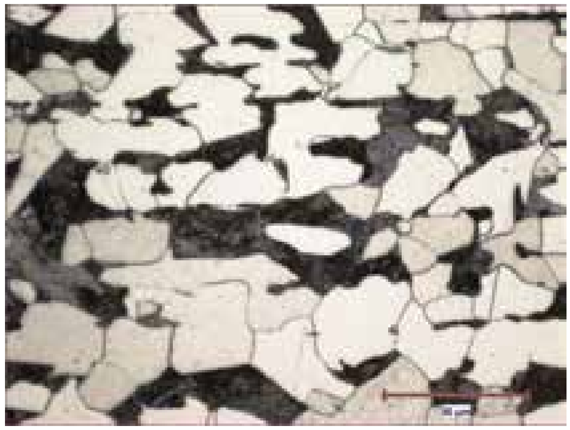
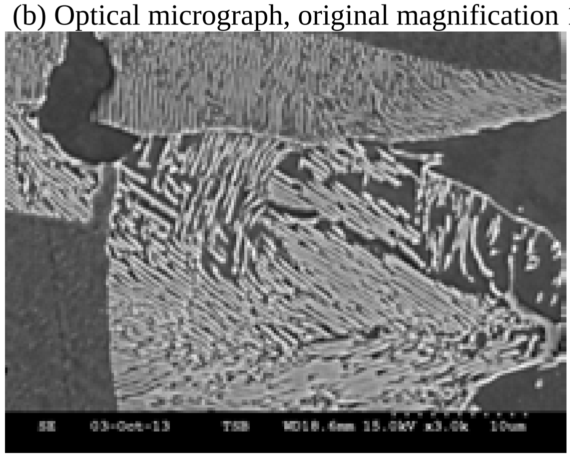
Coupon 20H - head	**Coupon 20S - shell**
 (a) Optical micrograph, original magnification 200X.	 (b) Optical micrograph, original magnification 200X.
 (c) Optical micrograph, original magnification 1000X.	 (d) Optical micrograph, original magnification 1000X.
 (e) SEM micrograph, original magnification 3000X.	 (f) SEM micrograph, original magnification 3000X.

Figure 15: Metallurgical cross-sections (Nital etch) of the PROX 44293 coupons.



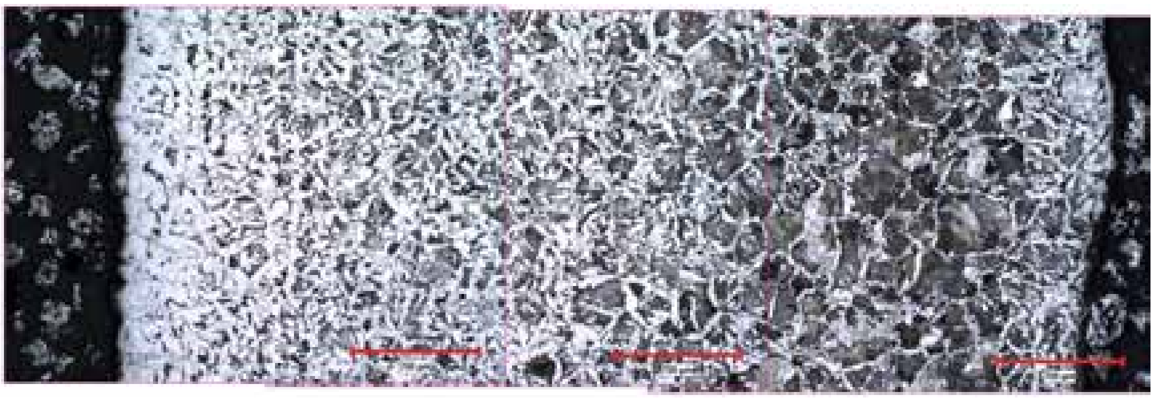
(a) Optical micrograph, original magnification 200X.

(b) Optical micrograph, original magnification 1000X.



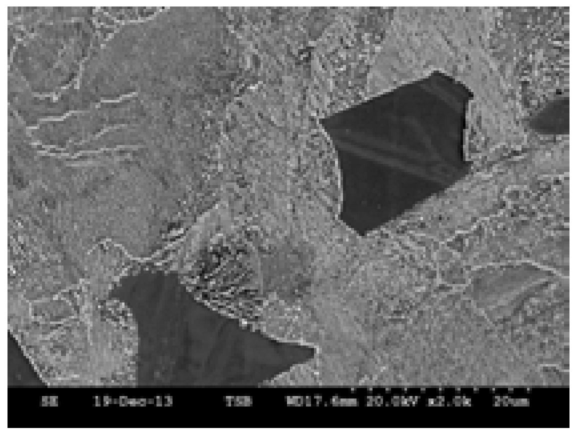
(c) SEM micrograph, original magnification 3000X.

Figure 16: Metallurgical cross-section (Nital etch) of coupon 24H (ACFX 76605 - head).

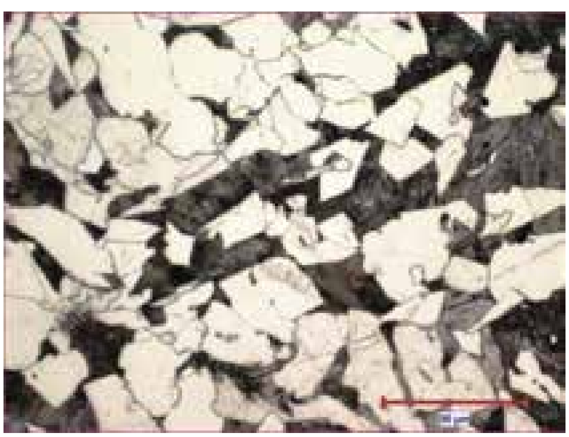


(a) Montage of optical micrographs showing the microstructural variation across the plate thickness (left-outer surface, right –inner surface, Nital etch, original magnification 25X).

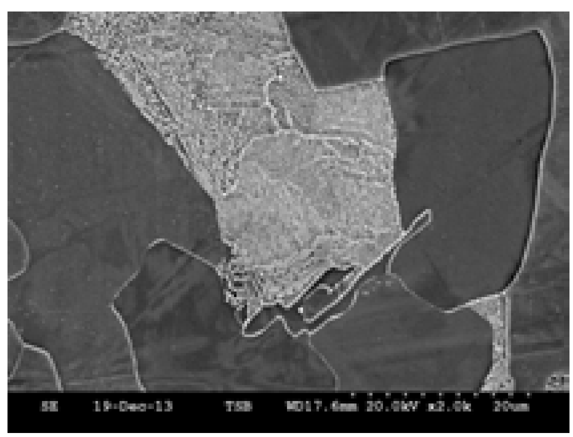
(b) Optical micrograph taken near the inner surface (Nital etch, original magnification 200X).



(c) SEM micrograph taken near the inner surface (Nital etch, original magnification 2000X).

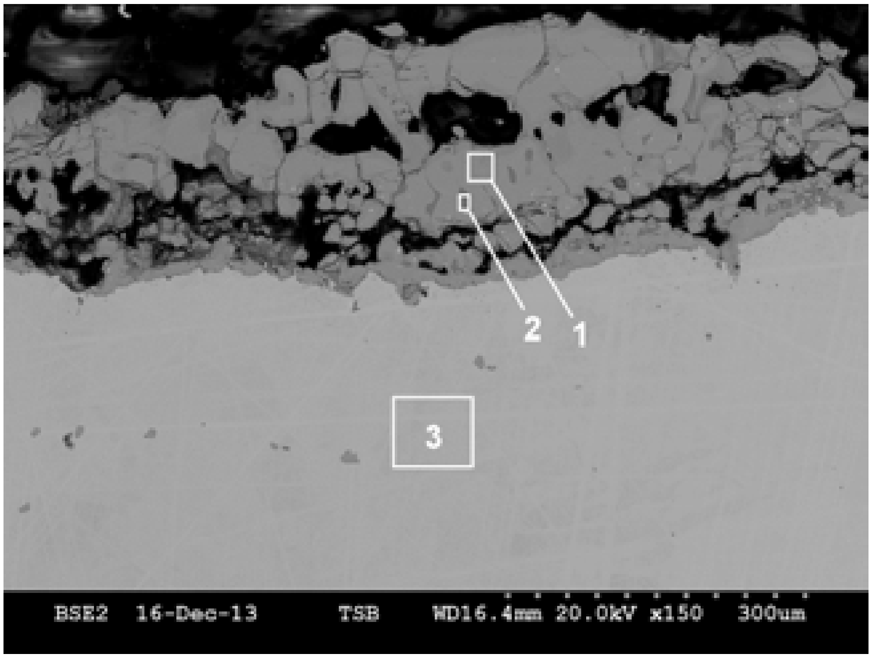


(d) Optical micrograph taken in the middle of the cross-section (Nital etch, original magnification 200X).



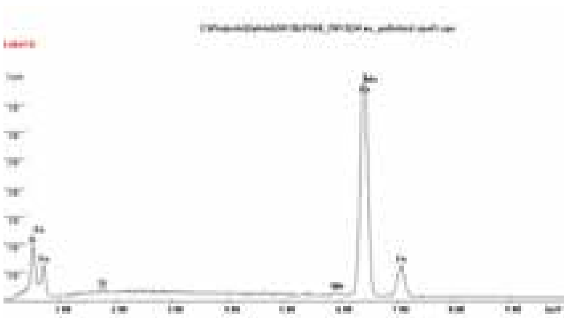
(e) SEM micrograph taken in the middle of the cross-section (Nital etch, original magnification 2000X).

Figure 17: Metallurgical cross-section of the WFIX 130571 shell coupon taken near the burn-through.

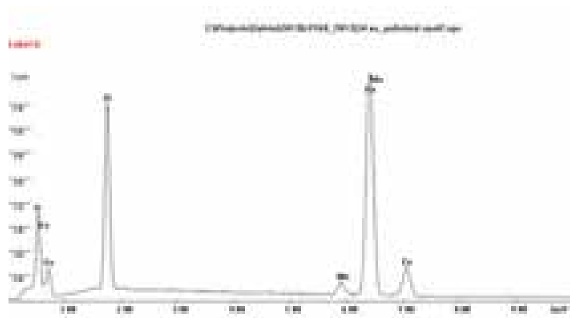


(f) SEM micrograph showing the oxide layer on the outer surface (back scattered electron mode, as-polished, original magnification 150X).

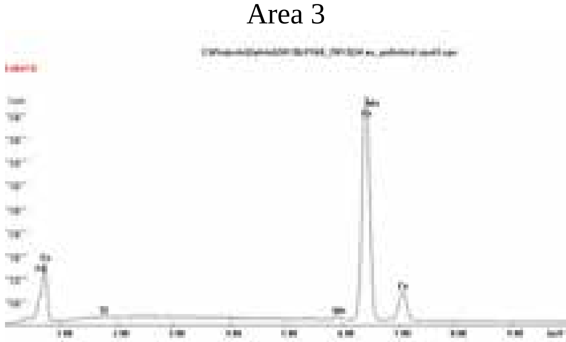
Area 1



Area 2

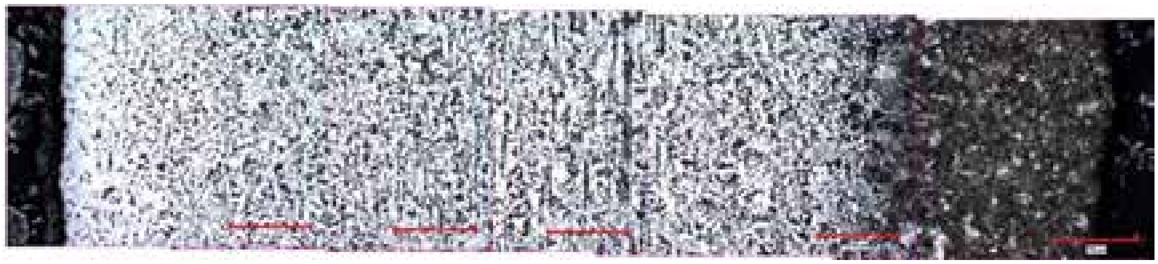


Area 3



(g) EDS spectra obtained from the areas highlighted on Figure 17f (O - oxygen, Si - silicon, Mn - manganese, Fe - iron).

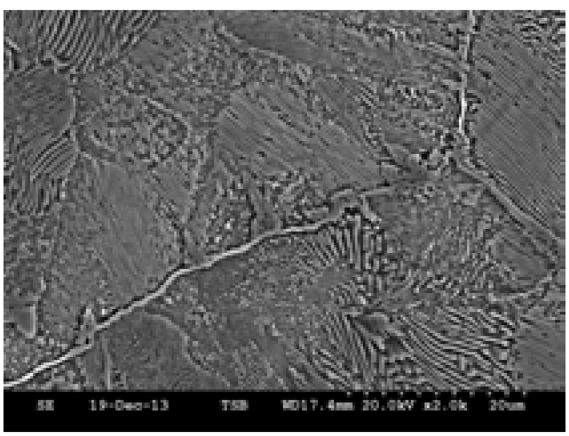
Figure 17: Metallurgical cross-section of the WFIX 130571 shell coupon taken near the burn-through.



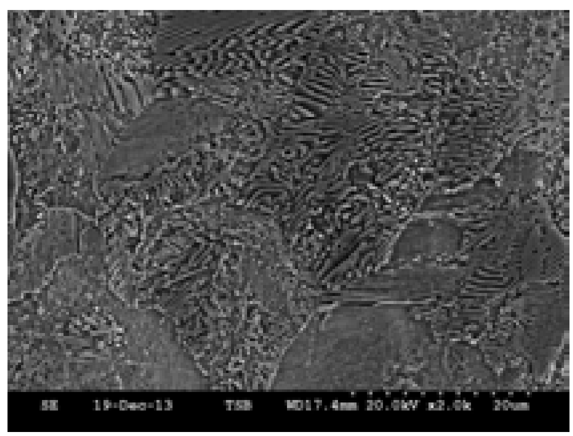
(a) Montage of optical micrographs showing the microstructural variation across the plate thickness (left- outer surface, right –inner surface, Nital etch, original magnification 25X).

(b) Optical micrograph taken near the inner surface (Nital etch, original magnification 200X).

(c) Optical micrograph taken near the inner surface (Nital etch, original magnification 1000X).



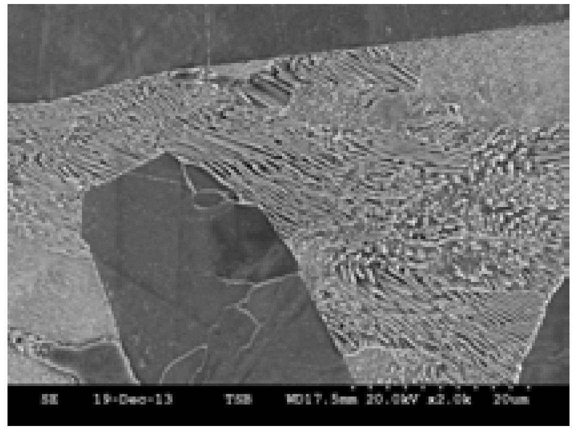
(d) SEM micrograph taken near the inner surface showing carbide phase decorating the prior austenite grain boundary (Nital etch, original magnification 2000X).



(e) SEM micrograph taken near the inner surface showing pearlitic microstructure (Nital etch, original magnification 2000X).

Figure 18: Metallurgical cross-section of the WFIX 130571 shell coupon taken away from the burn-through.

(f) Optical micrograph taken in the middle of the cross-section (Nital etch, original magnification 200X).



(g) SEM micrograph taken in the middle of the cross-section (Nital etch, original magnification 2000X).

Figure 18: Metallurgical cross-section of the WFIX 130571 shell coupon taken away from the burn-through.

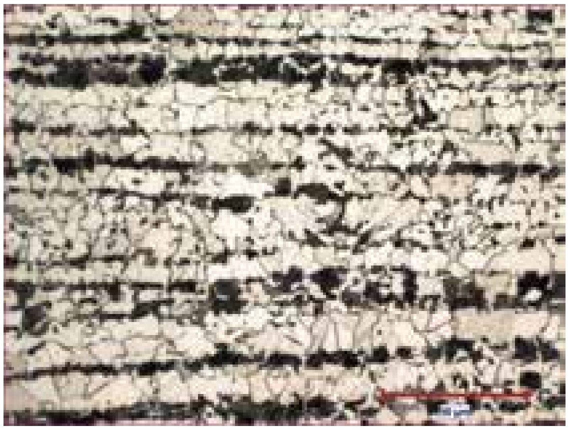
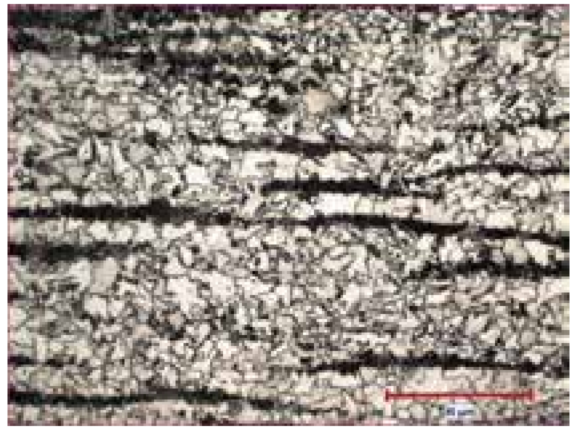
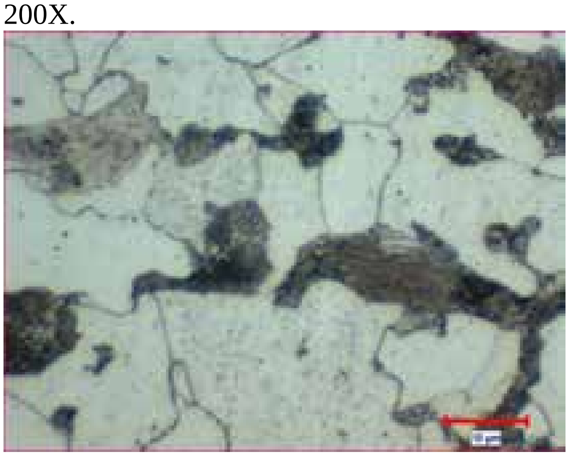
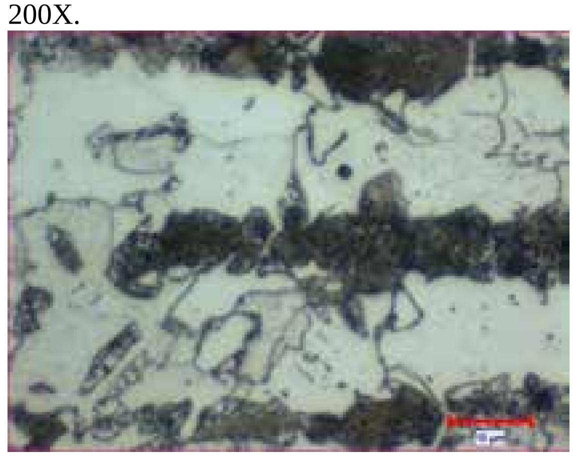
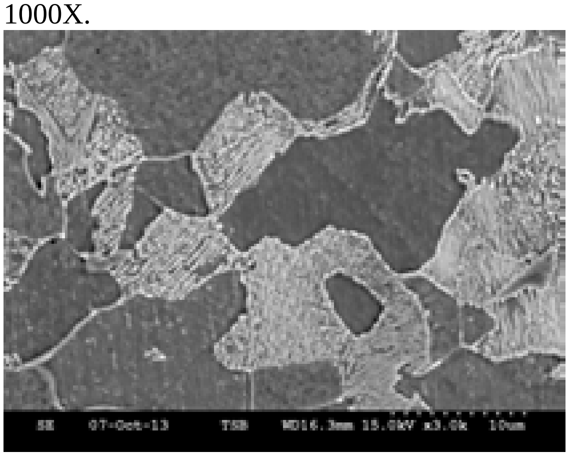
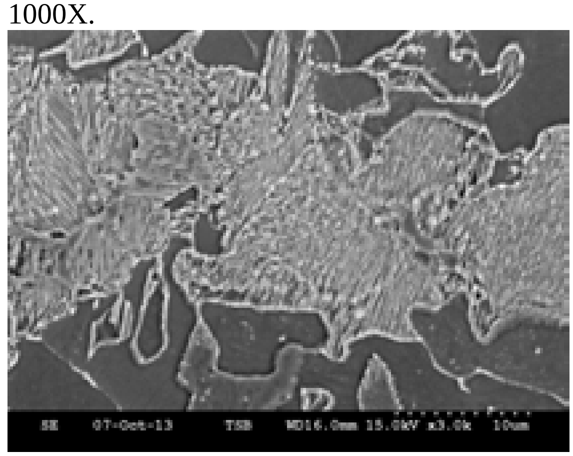
Coupon 40H - head	**Coupon 40S - shell**
 (a) Optical micrograph, original magnification 200X.	 (b) Optical micrograph, original magnification 200X.
 (c) Optical micrograph, original magnification 1000X.	 (d) Optical micrograph, original magnification 1000X.
 (e) SEM micrograph, original magnification 3000X.	 (f) SEM micrograph, original magnification 3000X.

Figure 19: Metallurgical cross-sections (Nital etch) of the CTCX 735572 coupons.

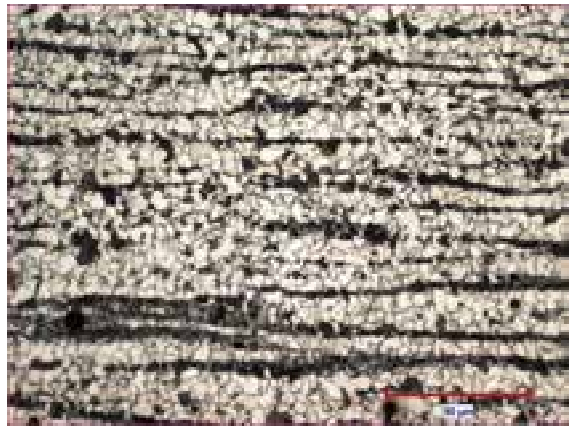
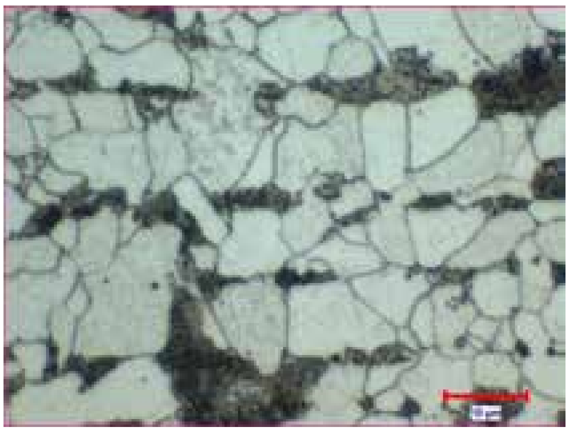
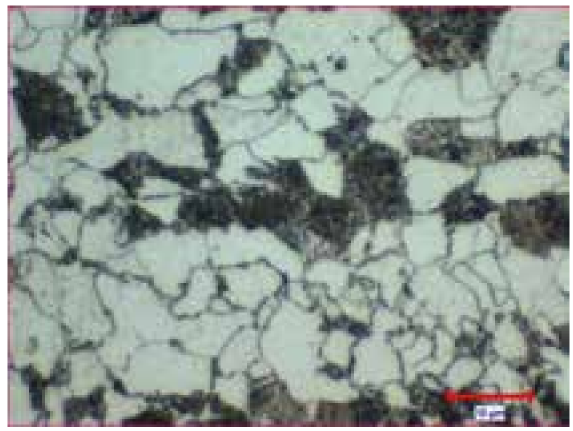
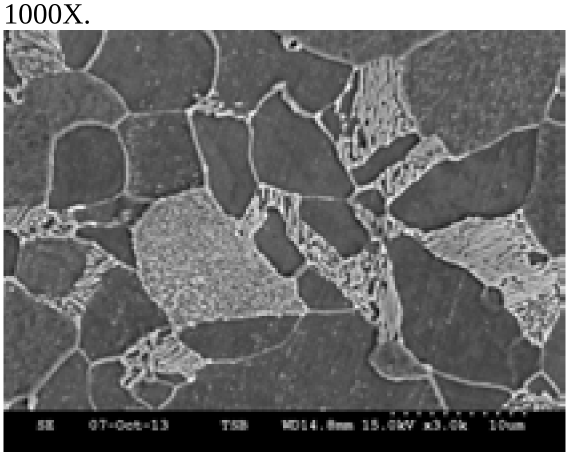
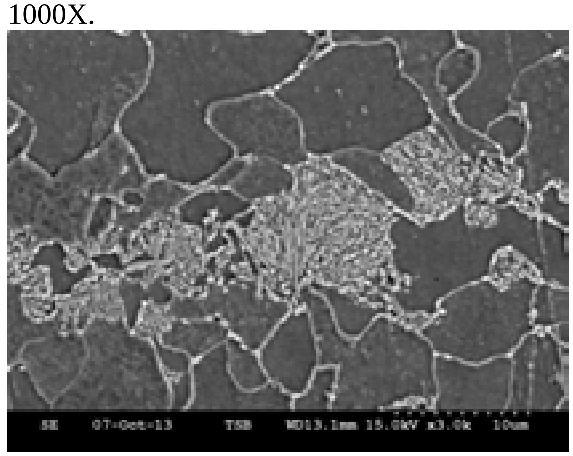
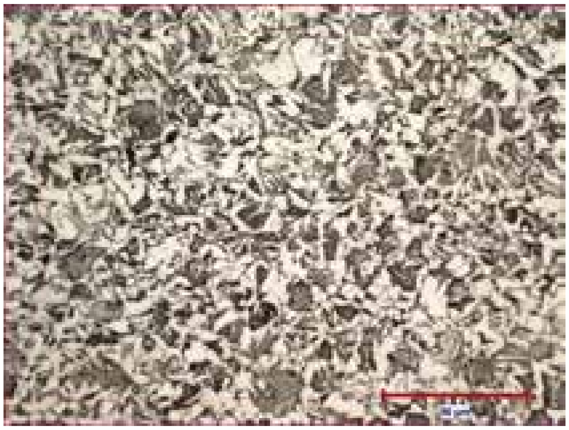
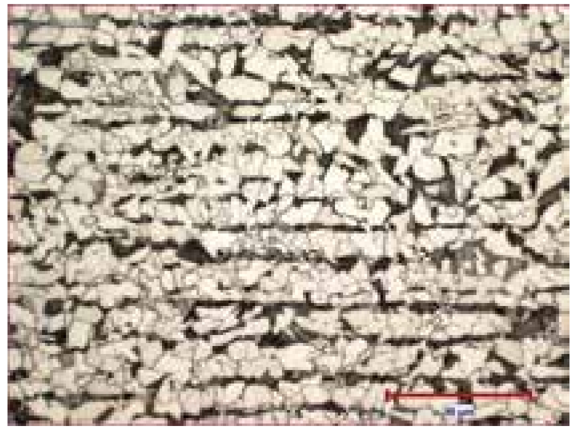
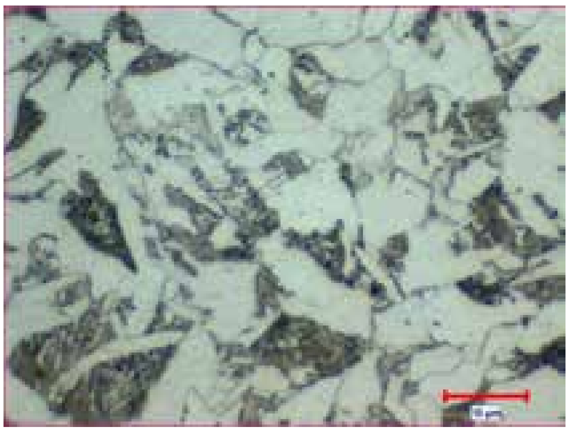
Coupon 58H - head	**Coupon 58S -shell**
 (a) Optical micrograph, original magnification 200X.	 (b) Optical micrograph, original magnification 200X.
 (c) Optical micrograph, original magnification 1000X.	 (d) Optical micrograph, original magnification 1000X.
 (e) SEM micrograph, original magnification 3000X.	 (f) SEM micrograph, original magnification 3000X.

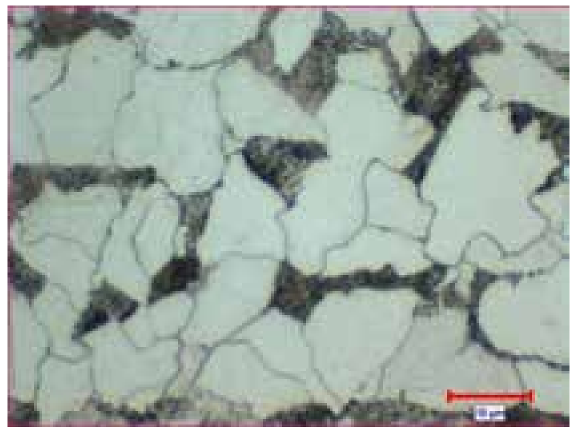
Figure 20: Metallurgical cross-sections (Nital etch) of the NATX 310515 coupons.

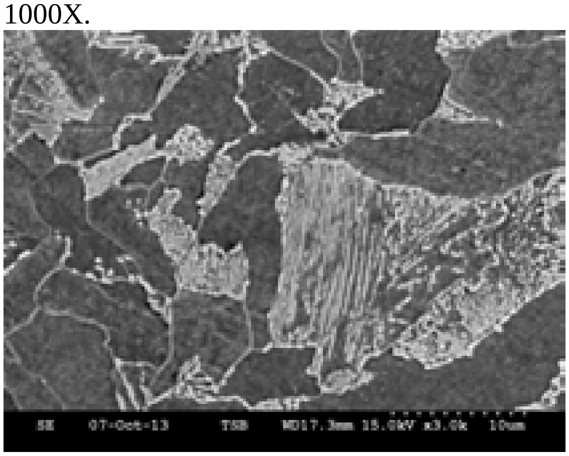
Coupon 59H - head	**Coupon 59S - shell**


(a) Optical micrograph, original magnification 200X.

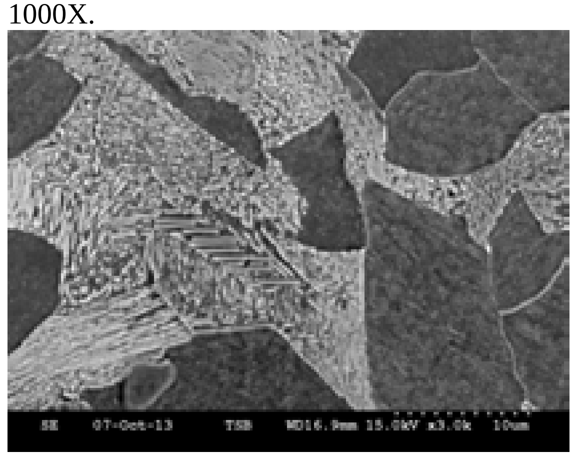

(b) Optical micrograph, original magnification 200X.


(c) Optical micrograph, original magnification 1000X.


(d) Optical micrograph, original magnification 1000X.



(e) SEM micrograph, original magnification 3000X.



(f) SEM micrograph, original magnification 3000X.

Figure 21: Metallurgical cross-sections (Nital etch) of the ACFX 79383 coupons.

Appendix A: Chemical Analysis Results for Tank Car Coupons

Table A-1: WFIX 130682 Coupons

Element	Coupon 8H - head		Coupon 8S - shell	
	Requirement per ASTM A516-70[A] (%)	Result (%)	Requirement per TC128-B[A] (%)	Result (%)
Carbon	0.25 max	0.16	0.26 max	0.20
Manganese	0.79-1.26	1.06	1.00-1.70	1.42
Phosphorus	0.025 max	0.012	0.025 max	0.021
Sulfur	0.015 max	0.012	0.015 max	0.005
Silicon	0.15-0.45	0.26	0.13-0.45	0.32
Vanadium	0.04 max	<0.005	0.084 max	<0.005
Copper	0.35 max	0.17	0.35 max	0.02
Nickel	0.43 max	0.06	no limit	0.02
Chromium	0.34 max	0.05	no limit	0.02
Molybdenum	0.13 max	0.02	no limit	<0.01
Aluminum	0.015-0.060	0.024	0.015-0.060	0.030
Niobium	0.03 max	<0.005	0.03 max	<0.005
Titanium	0.020 max	<0.005	0.020 max	<0.005
Boron	0.0005 max	<0.0005	0.0005 max	<0.0005
Nitrogen	0.012 max	0.006	0.012 max	0.007
Tin	0.020 max	0.01	0.020 max	<0.01
C_{Eq}	0.45 max	<0.37	0.55 max	<0.45
Cu+Ni+Cr+Mo	0.65 max	0.3	0.65 max	<0.07
Nb+V+Ti	0.11 max	<0.015	0.11 max	<0.015
Ti/N	4.0 max	<0.83	4.0 max	<0.71

[A] Refer to Table 5 in main body of report for details.

Table A-2: TILX 316641 Coupons

Element	Coupon 9H - head		Coupon 9S - shell	
	Requirement per ASTM A516-70[A] (%)	Result (%)	Requirement per TC128-B[A] (%)	Result (%)
Carbon	0.25 max	0.12	0.26 max	0.21
Manganese	0.79-1.26	1.31	1.00-1.70	1.43
Phosphorus	0.025 max	0.014	0.025 max	0.020
Sulfur	0.015 max	0.008	0.015 max	0.006
Silicon	0.15-0.45	0.31	0.13-0.45	0.33
Vanadium	0.04 max	<0.005	0.084 max	<0.005
Copper	0.35 max	0.24	0.35 max	0.03
Nickel	0.43 max	0.13	no limit	0.02
Chromium	0.34 max	0.10	no limit	0.02
Molybdenum	0.13 max	0.04	no limit	<0.01
Aluminum	0.015-0.060	0.036	0.015-0.060	0.028
Niobium	0.03 max	<0.005	0.03 max	<0.005
Titanium	0.020 max	<0.005	0.020 max	<0.005
Boron	0.0005 max	<0.0005	0.0005 max	<0.0005
Nitrogen	0.012 max	0.009	0.012 max	0.007
Tin	0.020 max	0.01	0.020 max	<0.01
C_{Eq}	0.45 max	<0.39	0.55 max	<0.46
Cu+Ni+Cr+Mo	0.65 max	0.51	0.65 max	<0.08
Nb+V+Ti	0.11 max	<0.015	0.11 max	<0.015
Ti/N	4.0 max	<0.56	4.0 max	<0.71

[A] Refer to Table 5 in main body of report for details.

Table A-3: ACFX 79709 Coupons

Element	Coupon 15H - head		Coupon 15S - shell	
	Requirement per ASTM A515-70[A] (%)	Result (%)	Requirement per TC128-B[A] (%)	Result (%)
Carbon	0.31 max	0.27	0.26 max	0.18
Manganese	1.30 max	0.46	1.00-1.70	1.13
Phosphorus	0.025 max	0.012	0.025 max	0.010
Sulfur	0.025 max	0.008	0.015 max	0.014
Silicon	0.15-0.45	0.25	0.13-0.45	0.19
Vanadium	0.04 max	<0.005	0.084 max	0.044
Copper	0.43 max	0.16	0.35 max	0.30
Nickel	0.43 max	0.12	no limit	0.22
Chromium	0.34 max	0.11	no limit	0.17
Molybdenum	0.13 max	0.03	no limit	0.05
Aluminum	not specified	<0.005	0.015-0.060	0.018
Niobium	0.03 max	<0.005	0.03 max	<0.005
Titanium	0.04 max	<0.005	0.020 max	<0.005
Boron	0.0015 max	<0.0005	0.0005 max	<0.0005
Nitrogen	not specified	0.008	0.012 max	0.010
Tin	not specified	0.01	0.020 max	0.02
C_{Eq}	0.47 max	<0.39	0.55 max	0.46
Cu+Ni+Cr+Mo	1.00 max	0.42	0.65 max	0.74
Nb+V+Ti	not specified	<0.015	0.11 max	<0.054
Ti/N	not specified	<0.63	4.0 max	<0.50

[A] Refer to Table 5 in main body of report for details.

Table A-4: PROX 44293 Coupons

Element	Coupon 20H - head		Coupon 20S - shell	
	Requirement per ASTM A516-70[A] (%)	Result (%)	Requirement per TC128-B[A] (%)	Result (%)
Carbon	0.25 max	0.18	0.26 max	0.23
Manganese	0.79-1.26	1.13	1.00-1.70	1.51
Phosphorus	0.025 max	0.016	0.025 max	0.014
Sulfur	0.015 max	0.007	0.015 max	0.012
Silicon	0.15-0.45	0.33	0.13-0.45	0.27
Vanadium	0.04 max	<0.005	0.084 max	0.034
Copper	0.35 max	0.02	0.35 max	0.02
Nickel	0.43 max	0.01	no limit	0.01
Chromium	0.34 max	0.12	no limit	0.16
Molybdenum	0.13 max	0.08	no limit	0.04
Aluminum	0.015-0.060	0.038	0.015-0.060	0.023
Niobium	0.03 max	0.005	0.03 max	<0.005
Titanium	0.020 max	<0.005	0.020 max	<0.005
Boron	0.0005 max	<0.0005	0.0005 max	<0.0005
Nitrogen	0.012 max	<0.005	0.012 max	0.005
Tin	0.020 max	<0.01	0.020 max	0.01
C_{Eq}	0.45 max	<0.41	0.55 max	0.53
Cu+Ni+Cr+Mo	0.65 max	0.23	0.65 max	0.23
Nb+V+Ti	0.11 max	<0.015	0.11 max	<0.044
Ti/N	4.0 max	1.0	4.0 max	<1.0

[A] Refer to Table 5 in main body of report for details.

Table A-5: ACFX 76605 Coupons

Element	Coupon 24H - head	
	Requirement per ASTM A515-70[A] (%)	Result (%)
Carbon	0.31 max	0.25
Manganese	1.30 max	0.50
Phosphorus	0.025 max	0.006
Sulfur	0.025 max	0.008
Silicon	0.15-0.45	0.29
Vanadium	0.04 max	<0.005
Copper	0.43 max	0.16
Nickel	0.43 max	0.13
Chromium	0.34 max	0.11
Molybdenum	0.13 max	0.03
Aluminum	not specified	<0.005
Niobium	0.03 max	<0.005
Titanium	0.04 max	<0.005
Boron	0.0015 max	<0.0005
Nitrogen	not specified	0.007
Tin	not specified	0.01
C_{Eq}	0.47 max	0.38
Cu+Ni+Cr+Mo	1.00 max	0.43
Nb+V+Ti	not specified	<0.015
Ti/N	not specified	<0.71

[A] Refer to Table 5 in main body of report for details.

Table A-6: WFIX 130571 Coupon

Element	Coupon 34S - shell	
	Requirement per TC128-B[A] (%)	Result (%)
Carbon	0.26 max	0.11
Manganese	1.00-1.70	1.23
Phosphorus	0.025 max	0.015
Sulfur	0.015 max	<0.005
Silicon	0.13-0.45	0.32
Vanadium	0.084 max	0.031
Copper	0.35 max	0.28
Nickel	no limit	0.12
Chromium	no limit	0.12
Molybdenum	no limit	0.02
Aluminum	0.015-0.060	0.035
Niobium	0.03 max	<0.005
Titanium	0.020 max	<0.005
Boron	0.0005 max	<0.0005
Nitrogen	0.012 max	0.008
Tin	0.020 max	0.01
C_{Eq}	0.55 max	0.38
Cu+Ni+Cr+Mo	0.65 max	0.54
Nb+V+Ti	0.11 max	<0.041
Ti/N	4.0 max	<0.63

[A] Refer to Table 5 in main body of report for details.

Table A-7: CTCX 735572 Coupons

Element	Coupon 40H - head		Coupon 40S - shell	
	Requirement per ASTM A516-70[A] (%)	Result (%)	Requirement per TC128-B[A] (%)	Result (%)
Carbon	0.25 max	0.17	0.26 max	0.26
Manganese	0.79-1.26	1.13	1.00-1.70	1.23
Phosphorus	0.025 max	0.015	0.025 max	0.011
Sulfur	0.015 max	0.007	0.015 max	<0.005
Silicon	0.15-0.45	0.32	0.13-0.45	0.31
Vanadium	0.04 max	<0.005	0.084 max	0.027
Copper	0.35 max	0.02	0.35 max	0.25
Nickel	0.43 max	0.02	no limit	0.12
Chromium	0.34 max	0.12	no limit	0.11
Molybdenum	0.13 max	0.09	no limit	0.04
Aluminum	0.015-0.060	0.035	0.015-0.060	0.036
Niobium	0.03 max	<0.005	0.03 max	<0.005
Titanium	0.020 max	<0.005	0.020 max	<0.005
Boron	0.0005 max	<0.0005	0.0005 max	<0.0005
Nitrogen	0.012 max	<0.005	0.012 max	0.007
Tin	0.020 max	<0.01	0.020 max	0.01
C_{Eq}	0.45 max	<0.40	0.55 max	0.53
Cu+Ni+Cr+Mo	0.65 max	0.25	0.65 max	0.52
Nb+V+Ti	0.11 max	<0.015	0.11 max	<0.037
Ti/N	4.0 max	1.0	4.0 max	<0.71

[A] Refer to Table 5 in main body of report for details.

Table A-8: NATX 310515 Coupons

Element	Coupon 58H - head		Coupon 58S - shell	
	Requirement per ASTM A516-70[A] (%)	Result (%)	Requirement per TC128-B[A] (%)	Result (%)
Carbon	0.25 max	0.17	0.26 max	0.20
Manganese	0.79-1.26	1.08	1.00-1.70	1.36
Phosphorus	0.025 max	0.009	0.025 max	0.012
Sulfur	0.015 max	0.006	0.015 max	0.008
Silicon	0.15-0.45	0.31	0.13-0.45	0.20
Vanadium	0.04 max	<0.005	0.084 max	0.040
Copper	0.35 max	0.04	0.35 max	0.26
Nickel	0.43 max	0.02	no limit	0.12
Chromium	0.34 max	0.11	no limit	0.11
Molybdenum	0.13 max	0.08	no limit	0.03
Aluminum	0.015-0.060	0.031	0.015-0.060	0.023
Niobium	0.03 max	<0.005	0.03 max	<0.005
Titanium	0.020 max	<0.005	0.020 max	<0.005
Boron	0.0005 max	<0.0005	0.0005 max	<0.0005
Nitrogen	0.012 max	0.005	0.012 max	0.008
Tin	0.020 max	0.01	0.020 max	0.01
C_{Eq}	0.45 max	<0.39	0.55 max	0.49
Cu+Ni+Cr+Mo	0.65 max	0.25	0.65 max	0.52
Nb+V+Ti	0.11 max	<0.015	0.11 max	<0.050
Ti/N	4.0 max	<1.0	4.0 max	<0.63

[A] Refer to Table 5 in main body of report for details.

Table A-9: ACFX 79383 Coupons

Element	Coupon 15H - head		Coupon 15S - shell	
	Requirement per ASTM A515-70[A] (%)	Result (%)	Requirement per TC128-B[A] (%)	Result (%)
Carbon	0.31 max	0.27	0.26 max	0.18
Manganese	1.30 max	0.42	1.00-1.70	1.22
Phosphorus	0.025 max	0.008	0.025 max	0.011
Sulfur	0.025 max	0.016	0.015 max	0.012
Silicon	0.15-0.45	0.19	0.13-0.45	0.23
Vanadium	0.04 max	<0.005	0.084 max	0.068
Copper	0.43 max	0.33	0.35 max	0.24
Nickel	0.43 max	0.21	no limit	0.13
Chromium	0.34 max	0.20	no limit	0.07
Molybdenum	0.13 max	0.07	no limit	0.03
Aluminum	not specified	<0.005	0.015-0.060	0.005
Niobium	0.03 max	<0.005	0.03 max	<0.005
Titanium	0.04 max	<0.005	0.020 max	<0.005
Boron	0.0015 max	<0.0005	0.0005 max	<0.0005
Nitrogen	not specified	0.007	0.012 max	0.008
Tin	not specified	0.02	0.020 max	0.02
C_{Eq}	0.47 max	<0.43	0.55 max	0.44
Cu+Ni+Cr+Mo	1.00 max	0.81	0.65 max	0.47
Nb+V+Ti	not specified	<0.015	0.11 max	<0.078
Ti/N	not specified	<0.71	4.0 max	<0.63

[A] Refer to Table 5 in main body of report for details.